



Aragonian stratigraphy reconsidered, and a re-evaluation of the middle Miocene mammal biochronology in Europe

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Abstract

The recently collected fauna of Armantes 1A in Chron C5Br of the Armantes section necessitates reinterpretation of the previous bio- and magnetostratigraphical correlations between the Armantes and Vargas sections (Calatayud–Daroca Basin, Central Spain) [W. Krijgsman, M. Garcés, C.G. Langereis, R. Daams, J. van Dam, A.J. van der Meulen, J. Agustí, L. Cabrera, A new chronology for the Middle to Late Miocene continental record in Spain, *Earth Planet. Sci. Lett.* 142 (1996) 367–380]. The long reversal in the Vargas section is now correlated to C5Br, instead of to C5Cr, on the basis of the biostratigraphical correlation of Armantes 1A to the faunas of Fuente Sierra 2 and 3 (in the Vargas section), which are situated in the basal part of the Middle Aragonian (MN5). This leads to the revised age of 16.0 Ma for the Early–Middle Aragonian (MN 4/5) boundary. Our age estimate of the MN5/6 boundary is maintained at ca. 13.75 Ma. The Vargas section is now considered to start in Chron C5Cn.2r and to end in C5Bn.1n. As a result of the revised correlation the duration of the time gap between the fossiliferous parts of Vargas and the younger Aragón section, previously estimated as ca. 1.5 Myr, is now reduced to less than 200,000 years. The tie points of the European mammal units (MN4–MN6) to the geomagnetic polarity time scale [F.F. Steininger, W.A. Berggren, D.V. Kent, R.L. Bernor, S. Sen, J. Agustí, Circum-Mediterranean Neogene (Miocene and Pliocene) marine–continental chronologic correlations of European mammal units, in: R.L. Bernor, V. Fahlbusch, H.-W. Mittmann (Eds.), *The Evolution of Western Eurasian Neogene Mammal Faunas*, Columbia Univ. Press, New York, 1996, pp. 7–46] are evaluated. Our age estimates of the MN4/5 and MN5/6 boundaries are compatible with the new magnetostratigraphic calibration of middle Miocene mammal zones in the Swiss Molasse basin [O. Kempf, T. Bolliger, D. Kálin, B. Engesser, A. Matter, New magnetostratigraphic calibration of Early to Middle Miocene mammal biozones of the North Alpine foreland basin, in: J.-P. Aguilar, S. Legendre, J. Michaux (Eds.), *Actes du Congrès BiochroM '97*, *Mém. Trav. E.P.H.E.* 21 (1997) 547–562]. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

In the Calatayud–Daroca Basin (prov. of Zaragoza) four mammal bearing sections have been sampled magnetostratigraphically [1,2] and correlated to the Geomagnetic Polarity Time Scale (GPTS) [3]. The Aragón, Armantes and Vargas sections are given in Fig. 1, the fourth section (Paje) is not discussed here. The micromammals sampled are presently under study.

The Armantes section (280 m) yielded 13 reversed and 12 normal polarity intervals and its correlation to the GPTS seems unambiguous [2]. The base of the section corresponds to Chron C5Cr and the top to C5An.2n. The single rodent fauna in the section known at the time, Armantes 1, is situated in Chron C5Br.

The Aragón section (170 m) is the type section of the Aragonian continental stage. Its correlation to the Armantes section and hence to the GPTS is unambiguous [2]. The section starts in Chron C5ADr (ca. 14.8 Ma) and ends in C5An.2r (ca. 12.5 Ma).

The Early–Middle Aragonian Vargas section (110 m) has been correlated to the Armantes section [1] assuming that the normal zones in the upper part of the Vargas section correspond to the lower normal zones in Armantes. Consequently, the top of the Vargas section was correlated to Chron C5Cn and the base to C5Dn. This correlation was based on the classical biostratigraphical correlation of Valdemoros 3B [4] in the upper part of the Vargas Section to Armantes 1. The Early–Middle Aragonian boundary drawn between the localities Vargas 2B and Vargas 2A (Fig. 1) was supposed to be situated in Chron C5Cr and estimated to be 17.26 ± 0.01 Ma in age. This boundary marks a major faunistic change which is also expressed in the distinction of MN4 and MN5 of the widely used mammal zonation in Europe (see below).

The above calibration of the Vargas section to the GPTS results in a time gap of approximately 1.5 Myr between the fossiliferous parts of the Vargas section and the younger Aragonian section covering magnetozones C5Bn.1n–C5Cn.1r [1]. However, detailed sedimentological and paleontological studies of the area carried out in the past years do not support the existence of such a large time gap. We therefore decided to resample the level of Armantes 1 which

is so crucial to the age determination of the Vargas section. The details of the litho- and biostratigraphy and sedimentology of the Aragonian type area will be published in the near future.

2. New sampling and correlations

In the early sixties de Bruijn collected large mammals (e.g. *Hispanotherium* [5]) and the rodent fauna Armantes 1 [4,6,7] from the very top of a lignitic grey marl, which was about 1 m thick and situated some 15 m above the base of his section Armantes A [6]. The marl has been indicated to us by de Bruijn in the field. It appeared that the outcrop has changed considerably due to erosion. The marl is now about 2 m thick in its center. As its top was very difficult to reach, only the base of the marl has been resampled in the summer of 1997 and yielded the Armantes 1A rodent fauna. Its composition differs considerably from that of Armantes 1, although the faunas are only two meters apart stratigraphically. The rodent faunas of Armantes 1 and the new level of Armantes 1A are listed in Table 1.

In Armantes 1A *Pseudodryomys simplicidens* is absent whereas it is frequent in Armantes 1, and in Armantes 1A *Eumyarion* is the predominant rodent whereas this cricetid is practically absent in Armantes 1. *Spermophilinus* sp. and *Peridyromys* aff. *jaegeri* are not represented in Armantes 1, although this fauna is much richer than the one of Armantes 1A. Armantes 1A is quite similar to the faunas of Fuente Sierra 2 and 3 (FTE2, FTE3) in the lower part of the Vargas section (Fig. 1). The three faunas share the following rodent species of stratigraphic interest: *Democricetodon* sp., *Pseudofahlbuschia* sp., *Eumyarion valencianum* (Cricetidae), and *Peridyromys* aff. *jaegeri* (Gliridae). The traditional correlation of Armantes 1 to Valdemoros 3B [4,6] (top Vargas section) was based on the evolutionary stage of the cricetid *Pseudofahlbuschia* [7]. However, revision of this lineage (now in progress) will show that the evolutionary changes of *Pseudofahlbuschia* are in good agreement with an age of Armantes 1 older than Valdemoros 3B. Armantes 1 and 1A are correlated to Zone Db and Valdemoros 3B to Zone Dc (Fig. 1), local zones which are (re)defined in a paper now in progress.

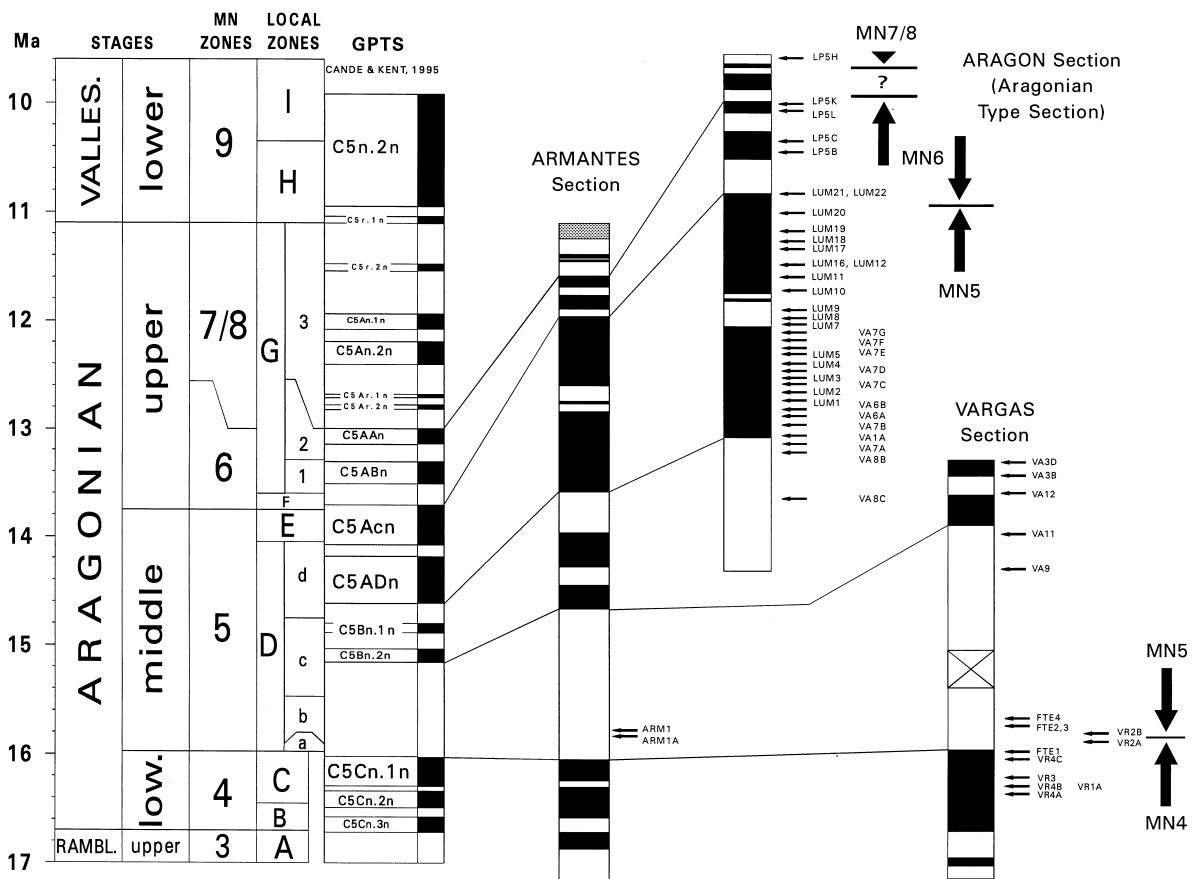


Fig. 1. Correlation of the polarity sequences of three Aragonian sections (for thicknesses see text) in the Calatayud–Daroca Basin (Spain) to the GPTS of Cande and Kent [3]. The correlations of the Aragonian type section and the Armantes section are after Krijgsman et al. [2], the correlation of the Vargas section is new. For the correlation of the Vallesian to the GPTS see Krijgsman et al. [1] and references therein. The thicknesses of local zones A, B and C are estimated on the base of sedimentation rates. The abbreviations refer to small mammal locality names (ARM = Armantes, FTE = Fuente Sierra, LP = Las Planas, LUM = Las Umbrias, VA = Valdemoros, VR = Vargas). The majority of the localities are situated in the measured sections, some have been correlated lithostratigraphically from small distances.

Since Armantes 1A is situated near the base of the long Chron C5Br and FTE2 and FTE3 are situated near the base of a long reversed interval as well, it is concluded that the latter represents Chron C5Br instead of Chron C5Cr [2]. Hence, the upper two normal polarity intervals of the Vargas section correspond to Chrons C5Bn.2n and C5Bn.1n, respectively (Fig. 1). This upward moving revision of the age of the Vargas section implies that the above mentioned time gap of approximately 1.5 Myr between this and the Aragonian section is reduced to maximally 200,000 years, since the uppermost locality Valdemoros 3D in the Vargas section lies in C5Bn.1n

(14.800–14.888 Ma) and the lowermost locality in the Aragón section lies in C5ADr (14.612–14.800 Ma).

3. Age of the MN4/5 boundary

In our sections three boundaries of MN units are present. The oldest one is the MN4/5 boundary which is situated between the levels of FTE1 and FTE2 in the Vargas section, and, a few hundred meters laterally, between Vargas 2A and 2B (VR2A and VR2B (Fig. 1) [1]. The onset of MN5 [8] is

Table 1

Cheek teeth of the rodent faunas of Armantes 1 and Armantes 1A

	ARM1	ARM1A
<i>Pseudodryomys simplicidens</i>	20	–
<i>Microdryomys koenigswaldi</i>	36	7
<i>Peridyromys</i> aff. <i>jaegeri</i>	–	3
<i>Spermophilinus</i> sp.	–	7
<i>Heteroxerus rubricati</i>	6	4
<i>Megacricetodon collongensis</i>	67	2
<i>Pseudofahlbuschia</i> sp.	29	7
<i>Eumyarion</i>	1?	26
<i>Democricetodon</i> sp.	10	3
Total sum of cheek teeth	169	59

characterized by progressive impoverishment of the rodent faunas (e.g. the extinction of the eomyid *Ligerimys*), and the expansion of *Hispanotherium* in the Iberian Peninsula. As a result of our new interpretation of the paleomagnetic data the age of the lower boundary of MN5 is changed. The previous estimation of 17.26 Ma [1] is here replaced by 16.0 Ma. Other MN-boundary ages are not affected. Thus, the MN5/6 and MN6–7/8 boundaries are maintained at 13.75 and 12.5–13.0 Ma, respectively [1].

4. Evaluation of the age estimates of MN4–MN6 tie points

In Steininger et al. [9] the latest marine–continental chronologic correlation scheme is given in which the Neogene European mammal units are tied to the absolute timescale. The scheme is based on dated mammal faunas (in terms of the MN zonation) that provide correlation tie points to marine biostratigraphies, the geomagnetic polarity time scale, or chronostratigraphic stages, or have isotopic ages. The MN4/5 boundary is estimated at 17.0 Ma and the MN5/6 boundary between 16.5 and 15.2 Ma [9], estimations that differ drastically from ours, 16.0 and 13.75 Ma respectively. In a recent paper the datings of MN4 and MN5 and a number of their tie points are reevaluated, and it is suggested that our MN5/6 age estimate has to be rejected on the basis of the evidence put forward [10]. In the fol-

lowing we will argue that the value of most of the MN4, MN5 and MN6 tie points to the time scale is very limited, and we will show that recent magnetostratigraphic results directly related to mammal faunas from Switzerland [11] are compatible with our present results and incompatible with schemes based on tie points [9].

4.1. MN4

According to Steininger et al. and Daxner-Höck et al. [9,10] MN4 lasted from approximately 18 to 17 Ma. Six tie points are presented as evidence. One tie point (Aliveri–Kymi) does not bear to our discussion as it concerns a correlation to an Eastern Mediterranean pollen zone. Tie point El Casots (Spain) with an inferred age of approximately 16.0 Ma is not incompatible with our age estimates of MN4 (Fig. 1), but it is incompatible with the scheme [9] for which it is presented. Orechov (Czech Republic) with an inferred age of older than 16.8 Ma does not fit well in our scheme, but the age estimate is not based on first order correlation [9,10]. The newly described MN4 fauna of Oberdorf (Austria) has been dated between 17.2 and 17.6 Ma, as it is found in a normal polarity interval that is correlated to Chron C5Dn [10]. However, the magnetostratigraphy consists of two successive polarity intervals only, and their correlation to the GPTS is based on the MN4 assignment of the mammal fauna. The magnetostratigraphy of the Turkish Gemerek section (showing two reversed zones separated by a normal zone only) with the Korlak and Gemerek tie points is criticized by Krijgsman et al. [12], who conclude that no reliable correlation to the GPTS can be made for the Gemerek section. Furthermore the correlations of the mammal faunas to the MN zonation are not firmly established [13], in spite of claims otherwise [9]. Nevertheless the section served as the estimate of the top of MN4 [9]. In the latter paper the Polish locality Belchatów C is considered the best tie point to estimate the base of MN4. The datings of the tuff overlying the mammal locality are 18.1 ± 1.7 , 17.05 ± 0.69 and 17.25 ± 0.4 ([9,10] and references therein), which in view of the large uncertainty ranges are unsuitable to estimate the age of any boundary in our opinion, and to calculate their mean without giving its uncertainty range (approximately 17.0 Ma in [10]). Our own

estimate of 17.0 Ma for the base of MN4 is based on the rate of deposition (adopted from the sections with magnetostratigraphy) in a composite section for which there is no magnetostratigraphy available and is, therefore, not considered very reliable.

4.2. MN5

There are nine MN5 tie points [9]. Two of them, Thenay and the reference locality for MN5 Pontlevoy-Thenay (France), which are correlated to the Langhian, are compatible with our present and earlier [14] results. Four tie points concern correlations to other stratigraphic units which lack dating: Sos and Rimbez (France) to the ‘Helvetian’ (parentheses in the original), Chios (Greece) and Dumlupınar (Turkey) to East Mediterranean pollen zones. One (Belchatów C) is unsuitable for the same reasons as given above for Belchatów B. Two Austrian tie points (Teiritzberg and Eibiswald) and a third (Obergänserndorf) added later [10] are not compatible with our scheme. Eibiswald does not serve anymore as a tie point, since the stratigraphical level from where the old mammal collection was recovered is unknown (F. Steininger, pers. comm., August 1998). Obergänserndorf and Teiritzberg are two Austrian MN5 mammal localities in the Korneuburg Basin in terrestrial to near-shore sediments of the Laa Formation which is placed in the Karpatian, the Central Paratethys stage equivalent to the uppermost Burdigalian. The sections in which the mammal faunas have been found, yielded only normal polarities. This interval has been correlated to Chron C5Cn.2n or C5Cn.3n in the following way: In the Molasse area north of the Korneuburg Basin the Laa Formation is overlain by sediments containing *Preaorbulina glomerosa*. This foram allows correlation with the global planktonic foraminiferal zone M5a used in the (Sub)Tropics [9] indicating the base of the Langhian which is equated to the base of the Badenian, the Central Paratethys stage above the Karpatian ([9], and references therein). The Burdigalian/Langhian boundary (= FAD of *P. glomerosa*) has been calibrated (outside the Paratethys) to Chrons C5Cn.2n–C5Cn.1n ([9], and references therein). Hence, the normal interval found in the Obergänserndorf and Teiritzberg sections are correlated to the chron C5Cn.2n or C5Cn.3n [10]. If all

this is correct, It follows from the GPTS that the MN5 localities have an age between 16.3 and 16.7 Ma. It is true that the reversed chron preceding and following C5Cn are quite long, so that its choice in view of the evidence given is a logical one. However, the dating of the Austrian MN5 mammal faunas is not the result of a first order correlation as the ones presented in the present paper (Fig. 1), but includes many steps and uses correlations and calibrations from outside the Paratethys. Presently the strength of the evidence for the age of these Austrian tie points cannot be evaluated, since the descriptions of the mammal faunas and the paleomagnetism have not been published yet.

Recently two more MN5 tie points have been added [10], the Swiss mammal faunas Eimättli (MN5, 16.7–16.0 Ma) and Oeschgraben (MN5/MN6, 15.15–14.8 Ma), the first found in, the second projected into the Fontannen section [15]. The data used by Daxner-Höck et al. [10] are, however, outdated by new results [11]. Eimättli is presently considered to belong to MN4 on the basis of additional material, and Oeschgraben as MN6. The polarity zones of the Fontannen section (900 m) are based on relatively few magnetic samples between which large gaps may exist [15]. Their correlation to the GPTS and hence the ages of the mammal localities are, therefore, ambiguous according to the most recent results [11].

4.3. MN6

There are seven MN6 tie points [9], of which three, Luc-sur-Orbieu and Veyran (France) and Steinberg/Goldberg (Germany), are compatible with our scheme. Paşalar and Çandır are not relevant to our discussion as they are correlated to East Mediterranean pollen zones only. The correlation of the Devinská Nová Ves fissure fillings (Czech Republic) to MN5 or MN6 is a matter of dispute even amongst the authors who present them as tie point for MN6 ([9] p. 30). But if the MN6 assignment and the estimated age of ca. 16.0 Ma is correct, this tie point is not compatible with our scheme. The age of the nearby Devinská Nová Ves sandhill locality is estimated as middle Badenian (younger than 15.2 Ma) on the basis of the correlation of the nearshore sands, from which the mammals were recovered, to

the middle to upper Badenian ([9], and references therein). The age estimate of ca. 15.2 ± 0.3 Ma [9] for the localities 24 and 24A (= Inönü 1) in Central Anatolia, Turkey is questionable. The age comes from the K–Ar date of a basalt flow which separates the Sinap Formation and the underlying Pazar Formation [16]. The distance between the place where the dated basalt sample was taken and the mammal localities is some 5 km. Steininger et al. ([9] p. 31) place the localities 24 and 24A in the Pazar Formation underlying the mentioned basalt flow, while Kappelman et al. ([16] p. 90) place them in the Sinap Formation “near the upper part of Pazar Formation” i.e. above the basalt flow, thus giving a maximal age for the base of Sinap Formation only. In view of these uncertainties one of the author’s (AJvdM) visited Inönü 1 this summer together with Dr. G. Saraç (MTA, Ankara) who originally discovered Inönü 1 and knows the stratigraphy of the area well. There is no doubt that Inönü 1 belongs to the Lower Sinap Formation [17], but it seems not sure to which part of that Formation. 200 m eastward, *Hipparion* beds overly the Lower Sinap Formation, possibly with an angular unconformity. The oldest occurrence of *Hipparion* in the Sinap area has been estimated at 10.46 Ma [16]. Finally Saraç disagrees with the “basal MN6” assignment ([9] and literature therein). On the basis of rhinoceros evolution Inönü 1 is younger than Çandır [17], which is placed in the upper part of MN6 ([9] and literature therein). An age of 15 ± 0.3 –10.46 Ma for Inönü 1 seems, therefore, to be the only realistic estimate for the moment and is not incompatible with our scheme. The 46 m thick Sansan section, of which the lower 15 m are practically unexposed, contains a long, reversed interval followed upward by two short normal ones. The long, reversed interval is correlated to chron C5Br [18]. Consequently the Sansan fauna is correlated to chron C5Bn.2n, so that its age is approximately 15 Ma. In our opinion the short paleomagnetic section of Sansan may be correlated to any middle Miocene part of the GPTS. In view of the Spanish evidence summarized in Fig. 1, the correlation of the long reversed zone of Sansan to chron C5Br [18] is highly unlikely. Biostratigraphically (*Megacricetodon gersii* and *M. minor* are common components) we correlate Sansan to the Las Planas 5B fauna (chron C5ABn) from the Aragonian type

section (Fig. 1), and consequently its numerical age would be approximately 13.6 Ma. This implies that the MN5/6 boundary in France would approach the value obtained in the Calatayud–Daroca Basin (ca. 13.75 Ma).

From this evaluation we conclude that the tie points which cannot be refuted on the present evidence and support the Steininger et al. [9] correlation scheme and are incompatible with our data, all have the disadvantage of being second or third order correlations. They do not support the rejection of any of our age estimates [10], which have been obtained through first order correlation between magnetostratigraphy and dense faunal successions and are not subject to the sometimes very large uncertainty that accompany radiometric datings. Often enough these error bars are forgotten, as for instance in the cases that the MN5/6 boundary is set at 15.1 Ma [19] or 15.2 [9], both ages being derived from the dating of the Ries impact event in S. Germany. The original age of the event is 14.8 ± 0.7 Ma (Gentner and Wagner 1969 in [11]) and is still used in Switzerland. Later datings have yielded mean values ranging from 14.5 to 15.1 Ma, of which “the most reliable date may be about 15.0 ± 0.1 Ma” ([19] p. 543).

5. Discussion

Our scheme is compatible with the new magnetostratigraphic calibration (supported by high quality diatomite dates) of middle Miocene mammal zones in the Swiss Molasse basin [11]. In fig. 10 of the latter publication the reliably calibrated parts of the MN zones are clearly indicated. On the basis of the Swiss record the MN4/5 boundary has an age between 16.9 and 16.1 Ma. The oldest Swiss MN5 faunas have been correlated to the top of Chron C5Cn.1n, while the oldest Spanish MN5 fauna (VR2B, Fig. 1) is in the lowermost part of Chron C5Br and the two youngest MN4 faunas (VR2A and FTE1) are very near the base of the latter chron. The overlap of the age estimates of the late MN4 and early MN5 faunas in the two areas is therefore in the order of 100,000 years only.

The MN5/6 boundary lies between 14.7 and 13.6 Ma according to the Swiss data [11], which is not

compatible with the above mentioned estimates of the boundary between 16.5 and 15.2 Ma [9,10], but is compatible with the age of 13.75 Ma on basis of the Spanish record [2].

Heissig [19] gives new correlations between the faunal sequences from the Upper Freshwater Molasse of Bavaria (S. Germany) and the Swiss Molasse basin [11]. A major improvement in the biostratigraphic correlations with the Swiss and Spanish records and the MN zonation is that the MN assignment of a number of localities antedating the Ries meteor impact event is changed from MN6 to MN5. The boulder layer ('Brockhorizont') associated with the impact is present at the base of the Upper Freshwater Molasse unit OSM F containing faunas which are assigned to MN6 as they are clearly younger than the typical MN5 of Ponlevoy-Thenay even though the level of Sansan (reference locality of MN6 and younger than the OSM F faunas) is not represented in the Upper Freshwater Molasse [19]. Only MN5 faunas are present in the unit immediately below the Ries boulder level. The ages accompanying the Bavarian sequence however, are not reliable since in our opinion too much importance is attached to the datings of the Ries event (see above).

According to Van der Meulen and Daams [14] two major environmental changes are evident from the Aragonian rodent succession: pronounced aridification with the onset of the Middle Aragonian which they estimated at ca. 16.5 Ma, and a cooling step between 15 and 13 Ma at the end of the Middle Aragonian (Zone E, Fig. 1). They extensively compared their relative humidity and temperature curves with paleoclimatic reconstructions based on other faunal and floral proxy evidence and on oxygen isotope curves, finding good correspondence between their results and those in the literature. The cooling step was subsequently dated to be 14.1 Ma [2], i.e. time-equivalent with the middle Miocene cooling step based on a main increase in $\delta^{18}\text{O}$ in the marine record [20]. The beginning of the aridification phase is now dated at ca. 16.0 Ma. The new datings of the Aragonian and its recently expanded faunal record will enable the comparison of Miocene paleoclimatic reconstructions based on marine and terrestrial proxies in unprecedented detail.

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